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13. ABSTRACT (Maximum 200 words)  <p>This grant has supported the development of infrared interferometry, studies of atmospheric transmission and image distortion, and the resolution and study of stars and material surrounding them, with the general goal of improving astrometry and hence determination of stellar positions. Substantial progress has been made, including determination of atmospheric distortions of infrared transmission and its variation with time, altitude location of major atmospheric distortions, correlation of radio and infrared measurements, and studies of possible change in apparent positions of stars due to stellar behavior. Findings are outlined briefly in this report. Rather complete discussion of the findings are in the 36 scientific publications supported by the grant. They are listed here and identified as to which of the several goals of the investigation they primarily apply.</p>				
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Final Technical Report of OCNR Grant N00014-89-J-1583  
for the Support of Infrared Spatial Interferometry

Introduction

The grant N00014-89-J-1583 began on January 15, 1989 and ended December 31, 1995. Its purpose was the exploration and development of infrared spatial interferometry at wavelengths near 10 microns. The development had several goals. One was the general development of technology and exploration of performance of infrared interferometry. A second was study of fluctuations in pathlengths through the atmosphere and their characteristics, particularly as they affect the quality of interferometry or imaging through the atmosphere. A third was a coordination of measurements by radio interferometry of masers near stars with infrared interferometric measurements to determine where the masers occur with respect to the star, and with relevance to astrometry particularly in mind. A fourth was a general exploration of stellar characteristics with the infrared interferometer, with their relevance to astrometry particularly in mind. Progress in these various directions made during the term of the grant are discussed below.

Atmospheric Results

Fluctuations in the local index of refraction of the atmosphere have generally been modeled by the Kolmogorov approximation. This assumes an atmosphere of uniform average density, temperature, and humidity, and with no boundaries. This model predicts that the squares of differences between atmospheric indices of refraction at points separated by a distance R is proportional to  $R^{2/3}$ . It is also usually assumed that there is an upper limit to the distance between points for which the index refraction difference continues to increase. This upper limit is generally called the outer scale. There have been previously reported measurements indicating

that the Kolmogorov predictions are accurate representations of the actual behavior of the atmosphere and that the outer scale is very large, of the order of a kilometer. Results from the present investigation show that in fact the outer scale is often rather short, of the order of 10 meters or a few tens of meters, and that there are substantial deviations from the Kolmogorov predictions. The deviations are in the direction of making the build up of differences in index refraction between two points in the atmosphere somewhat slower than that predicted Kolmogorov model. All these results are quite favorable to imaging through the atmosphere and to interferometry. This is because previous expectations, based on the Kolmogorov approximation and on measurements in telescopes with rather limited size such as one or two meters diameter, would have predicted somewhat larger fluctuations than has been found here for large telescopes or interferometers with long baselines..

Our results are of course limited to the particular place of observation, namely the Mt. Wilson Observatory. However, measurements which have recently have been made at a number of other observatories indicate that an outer limit of the order of 10 meters or a few tens of meters is rather common and that in addition there are variations from the Kolmogorov increase of index refraction difference with distance in the same direction we have found on Mt. Wilson. How much the rate of increase of index of refraction differs is still under discussion, and this difference may be less at visible wavelengths than in the infrared. However, such differences do occur.

A second finding of the atmospheric measurements which is very encouraging for the future of imaging through the atmosphere is that a large fraction of the "poor seeing," or fluctuations in atmospheric pathlengths, is associated with a ground layer of the atmosphere not higher than about 40 meters. This occurs particularly when wind velocities are low, i.e., not higher than about 5 meters/second. On Mt. Wilson in particular, we find that about 2/3 of the disturbances in

pathlengths through the atmosphere come from a ground layer of atmosphere extending not higher than about 40 meters. These effects can fortunately be or corrected by local measurements of the lower level properties of the atmosphere, or they can be more or less eliminated by mounting telescopes high above the ground when this is practical.

Publications resulting from our work on atmospheric properties and pathlength fluctuations include numbers 8, 12, 13, 15, 16, 26, 27, and 33 of those listed at the end of this discussion.

### Instrumentation

There has of course been a great deal of work on development and testing of the interferometer, including upgradings and modifications of the system which had been originally put together. Discussion of the instrument, its upgrading, and its performance are given in publications 2, 4, 10, 11, 18, 19, 20, 21, and 24 listed at the end of this discussion.

### Astrometry

Although measurements of fluctuations in the atmosphere give a considerable amount of information of importance to astrometry, additional rather direct astrometric measurements have been made, including one particular case of a comparison between SiO masers as measured with radio interferometry and the radius of the dustshell around the star with which the masers were associated. This shows that SiO masers are in fact rather close to the surface of the star and where dust just begins to form. Discussions pertinent to these aspects of astrometry include publications 28, 29, 30, 31, and 35 in the list following this discussion.

## Stellar Structure and Behavior

The size of the stars, formation of dust around them, distribution of this dust, and the changes of stars with time have been studied with the infrared interferometer. It appears that the sizes of stars can probably be better determined from infrared interferometry than from visible interferometry. It has been well known that stars vary in intensity or magnitude, and recently it has been found that some of this variation is associated with hot spots on the stars which change the center of the total radiation. We have shown that most of the variation in intensity of the bright star Betelgeuse is in fact associated with changes of temperature rather than size. These changes in temperature appear to be localized spots, and hence can change the center of gravity of the visible light emission, which affects high precision astrometry. The infrared is much less affected by such changes in temperature because it varies more or less linearly with temperature whereas visible light varies exponentially with temperature. Limb darkening due to the stellar atmosphere is also a less troublesome effect in the infrared than it is in the visible light, which is another reason why infrared measurements can give better determinations of the actual size of stars as well as their center of gravity.

We have found that many stars emit dust more or less episodically and irregularly. This dust is part of the reason their luminosity appears to change in the visible region, and can also cause some shift in the center of gravity of the visible light, which may affect astrometry.

In addition to the above comments concerning our study of stars, we have done extensive work on examining where the dust forms around stars, its distribution and temperature, and to some extent its composition. Such studies of stars are reported in publications 3, 5, 6, 7, 9, 14, 17, 23, 25, 32, 34, and 36 in the list following this discussion.

### Collaborators

Students who have made significant contributions to work on this grant include David Hale, Peter McCullough, Everett Lipman, and John Monnier.

We have welcomed collaborators from other institutions who were interested in working with us on these technical and scientific problems. They include Dr. Thomas Geballe of the United Kingdom Infrared Telescope in Hawaii, who has measured certain infrared characteristics of the stars we have been studying in order to add to the detail with which interpretations of our results can be made. In addition, Dr. Lincoln Greenhill of the Smithsonian Astronomical Observatory in Cambridge, Massachusetts has collaborated with us in examining the relation between SiO masers about stars and the stellar characteristics. Dr. Robert Trehaft of the Jet Propulsion Laboratory has collaborated with us in analyzing characteristics of the atmosphere, particularly the disturbed ground layer of the atmosphere, and the possibilities of accurate astrometry. Dr. Cuno Degiacomi of the University of Köln, Germany has collaborated with us in upgrading of the technology of the telescopes and in the measurement of stars. Dr. Bruno Lopez of the Observatory of Nice in France has also collaborated with us in examination of the variation of stars such as o Ceti with time and their deviation from sphericity.

### Summary

Overall we believe that work which this grant has supported has made a very substantial impact on the technique of interferometry and particularly its use in the mid-infrared. We appreciate very much the important support provided by OCNR which has made this work possible.

## Publications

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12. "Atmospheric Pathlength Fluctuations in the Infrared Spatial Interferometer," C.H. Townes, *Adaptive Optics for Large Telescopes Technical Digest* (Optical Society of America, Washington, D.C.) **19**, 48 (1992).
13. "Atmospheric Fluctuations — Empirical Structure Functions and Projected Performance of Future Instruments," M. Bester, W.C. Danchi, C.G. Degiacomi, L.J. Greenhill, and C.H. Townes, *ApJ* **392**, 357 (1992).
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